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DETERMINATION OF JET-BOUNDARY CORRECTIONS TO COWLING-FLAP-OUTLET PRESSURES BY AN ELECTRICAL ANALOGY METHOD

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DETERMINATION OF JET-BOUNDARY CORRECTIONS TO COWLING-FLAP-OUTLET PRESSURES BY AN ELECTRICAL-ANALOGY METHOD

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SUMMARY

In order to determine jet-boundary corrections to cowling-flap-outlet pressures, corrections to the velocities near a cowling-flap tip have been studied by an electrical-analogy method. The presence of the low-energy air leaving the flap opening was taken into account by so shaping the nacelle model that its outer surface represented the stream surface leaving the flap tip.

Copper was found unsatisfactory for use as electrode material. Good accuracy was obtained with chromium-plated copper for tank electrodes and platinum wire for the solution contacts.

An 8-percent velocity correction was found for a typical nacelle in the LMAL 16-foot high-speed tunnel, corresponding to a correction of about 0.25 times free-stream dynamic pressure at the flap outlet. The results agreed approximately with the corrections calculated by Lamb's method for an equivalent source-sink ovoid.

INTRODUCTION

Some uncertainty has existed regarding the magnitude of the jet-boundary effect on the cowling-flap-outlet pressures (and hence, on the available cooling pressures) in tests of air-cooled engine installations in the LMAL 16-foot high-speed tunnel. The difficulty in analysis results not only from the three-dimensional character of the flow but also from the presence of the low-energy nonpotential flow out of the flap opening.

In order to obtain a practical solution of the problem, the presence of the low-energy-air layer may be taken into account by considering the nacelle radius to be increased by an amount equal to the displacement thickness of this layer. The potential flow about this new body, however, although perhaps amenable to analysis, is very difficult to derive; and the results that might be calculated for a simpler body like the Rankine ovoid (reference 1) were considered of questionable applicability. It was therefore considered expedient to solve the problem in the electrical tank by use of the analogy between the flow of current and the potential flow of air. The method consisted of measuring and comparing the flows about a given nacelle model in four tanks (representing wind tunnels) of different size, for the largest of which the correction was so small that it could be adequately calculated by an approximate method.

The present paper presents results on the jet-boundary corrections and a somewhat detailed discussion of some of the techniques involved. The existing literature on the subject is relatively unsatisfactory in this respect.

THEORY OF METHOD

Electrical analogy.- The electrical analogy arises directly from the similarity of the differential equations for the irrotational flow of air and the differential equations for the flow of electric current in a uniform conducting medium. Both equations are Laplacian:

$$\nabla^2\phi = 0$$

$$\nabla^2 E = 0$$

where ϕ and E are the velocity potential and the electric potential, respectively. It follows that, for similar boundaries and boundary conditions, the velocity of fluid flow is analogous to the electric current in both magnitude and direction, or inasmuch as, with uniform conductivity of the medium, the current is proportional to the voltage gradient, local velocity is directly analogous to local voltage gradient. The

boundary conditions for these tests are merely (1) the flow is uniform and parallel to the axis at large distances upstream and downstream from the body, and (2) there is no velocity component normal to the body or the tunnel wall. For the electrical tank, the first condition is satisfied by using a tank of sufficient length, with electrodes completely covering the ends of the tank and at right angles to the tank axis. The second condition is satisfied by using insulating material for the body and for the tank walls.

Theory of model-nacelle design.- The flow of cooling air through an air-cooled engine cannot be simulated by - what might appear as an obvious analogy - the flow of electric current through a high-resistance membrane in the nacelle model. Such an internal resistance would result only in a flow as shown in figure 1(a), quite unlike the true flow (fig. 1(b)), because a discontinuity in total pressure, such as exists at the edge of the cooling-air layer, cannot be represented in the electrical tank. The model was therefore extended to a continuation of the flap (fig. 2) in order that the flow of current about this region might represent the flow of the external air in the neighborhood of the flap exit.

In order that the flow near the cowl entrance might be simulated, a passage was provided along the model axis of such area that the current flowing into the entrance corresponded to the cooling-air flow. The net cross-sectional area of the model at every station thus corresponds to the cross-sectional area of the engine nacelle plus the displacement area of its surrounding low-energy air; that is, the amount by which the outer streamlines are displaced outward as a result of the reduced velocities in the inner layers.

Because of the jet-boundary effects on the amount of internal flow and on external pressures, the design of the model should probably not be exactly the same for all four tanks. Inasmuch as no means of determining these variations was available and a test showed that a 20-percent blocking of the internal passage caused only a 0.3 percent increase in external gradient, the matter was not further considered.

For best representation of the external flow, the model should not taper to zero cross section but should continue indefinitely downstream with a cross-sectional area equal to the displacement area of the wake:

$$A^* \approx \frac{D}{2q_o}$$

where

A^* displacement area of wake

D nacelle drag

q_o free-stream dynamic pressure

The rear cross section of the model was accordingly made large enough to correspond, by this equation, to the large drag coefficients measured for flap-open conditions. The length of the model, however, was for practical purposes only four times its diameter. Although the model was somewhat too short to represent effectively a model of infinite length, the error involved was estimated to be small.

<u>Basis for computing jet-boundary correction</u>.- The suction in the flap opening is assumed to be determined by the velocity of the flow over the flap tip, according to the equation

$$p - p_o = \frac{1}{2}\rho\left(V_o^{\,2} - v^2\right)$$

or

$$P \equiv \frac{p - p_o}{\frac{1}{2}\rho V_o^{\,2}} = 1 - \left(\frac{v}{V_o}\right)^2 \qquad (1)$$

where

p_o free-stream static pressure

p local static pressure

V_o free-stream airspeed

V local airspeed

ρ density

P pressure coefficient

and the jet-boundary effect on exit pressures is accordingly assumed to depend only on the jet-boundary effect on the velocities in this region.

As has already been noted, the local velocity corresponds to the local voltage gradient, and the ratio V/V_o corresponds to the ratio of the voltage gradient along the model in the region of the flap tip to the voltage gradient in the "free stream" ahead of the model. From comparisons of the V/V_o ratios thus found in the different tanks, the jet-boundary corrections in the smaller tanks are found relative to the correction in the largest tank, which can be obtained accurately by a simple calculation.

APPARATUS AND METHODS

Tanks.- Four semicylindrical tanks were used, all about 50 inches long, with diameters of 5.5 inches, 8 inches, 11 inches, and 15.5 inches, respectively. The tanks were made of celluloid sheets curved to fit into heavy wooden forms and sealed together with acetone. A sketch of the 8-inch tank is shown in figure 3.

Nacelle model.- The nacelle model (fig. 2), 3 inches in diameter, was cut from a Micarta cylinder and given several coats of spar varnish. Its size, in proportion to the 8-inch tank, corresponded to a typical nacelle in the LMAL 16-foot high-speed tunnel. In order to measure the potentials near the flap opening, six small contacts made of flattened No. 24 platinum wire, were brought through the surface, about 0.2 inch apart, along a meridian. Fixing the contacts on the model in this way is much more accurate, for the present purpose, than using a movable external contact. The platinum wires were soldered to copper leads, which were brought out through a small glass tube into which they were sealed with paraffin to insure that no motion of the external leads could be imparted to the contacts. The model was suspended from

a triangular board that rested on top of the tank; three leveling screws were used to adjust the height and inclination of the nacelle model so that it would be exactly half immersed in the tank.

Electrical circuit.- The circuit, which is essentially a Wheatstone bridge, is shown in figure 4. When the bridge is balanced, as indicated by silence in the headphones, the voltage at the contact is given by the relation

$$\frac{\text{Voltage at contact - voltage at left electrode}}{\text{Voltage between electrodes}} = \frac{R_1}{R_1 + R_2}$$

All voltage differences between pairs of adjacent contacts are thus found relative to the voltage between the end electrodes.

A variable capacitance across one of the resistance arms was introduced to balance the stray circuit and solution capacitances. In order to avoid excessive dielectric losses, only mica and air condensers were used. Although absolutely essential for getting a reading, the capacitance was at no time large enough to affect the impedance of its circuit, that is, to make inaccurate the use of the simple resistance ratio in the preceding equation.

The bridge was fed by a 5-watt power oscillator, operated for most of the tests at 1000 cycles. The headphones were, for high sensitivity, selected to have a high impedance (20,000 ohms) comparable with the impedance of the circuit. The two 10,000-ohm resistance boxes were calibrated to 0.1 ohm.

Electrodes.- Previous workers (for example, see references 2, 3, and 4) with the method of electrical analogy have used electrodes of copper, brass, or aluminum. Few difficulties in the use of these metals have been reported, although the necessity for frequent polishing of the electrodes and for the use of acid in the solutions has been noted. In the present study, some attempts were made to use copper for the end electrodes and for the contact wires; however, the readings

were found to drift at large and irregular rates and the copper surfaces quickly lost their polish. Satisfactory results were obtained with chromium-plated copper sheets for the end electrodes and platinum wires for the contacts. Even with these metals, some slow drift was almost always observed, but the potentials of the platinum contacts always drifted up or down together; the cause of the drift was therefore probably elsewhere, occasioned either by chemical action at the end electrodes or by temperature or concentration variations.

With regard to electrode material, it is of interest to note that copper was long ago discarded for measurements of the conductivity of solutions. Platinized platinum is used almost exclusively for such measurements, although smooth platinum has been used successfully for solutions of low conductivity and the less noble metals, silver and nickel, have been found reasonably satisfactory for less precise work.

Distance standard.- As a primary distance standard for the determination of the free-stream potential gradient in the solution, the instrument shown in figure 5 was used. It has a platinum contact attached to a sliding arm which can be moved precise distances of 1 inch and 2 inches along the tank, by means of carefully ground spacers. A more convenient secondary standard, calibrated against the primary standard, was made of a pair of platinum contacts suspended from the arms of an inverted glass U (fig. 6).

The potential gradient as determined with these standards was nearly 1 percent less than the ratio of the potential difference between the end electrodes to the distance between the end electrodes. The difference was tentatively ascribed to the known tendency of the end electrodes to act as series capacitances, wherein polarization sets up a counter-voltage analogous to that set up by a charged condenser. An effort was made to eliminate the capacitance effect by using higher frequencies, since such an effect should decrease with the inverse square of the frequency; however, the gradient was found to rise almost linearly with frequency, with a total gradient increase of 0.6 percent in the range from 1000 cycles to 5000 cycles (the highest frequency that was distinctly audible).

Series inductances were also tried (fig. 7), of such magnitude that the effective electrode capacitances could be balanced (that is, a maximum gradient could be found) with a frequency in the neighborhood of 1000 cycles. Inasmuch as the inductances had appreciable resistances relative to the tank resistance, a direct solution of the circuit shown is not possible; the potentials could be calculated, however, by simultaneous solution of the equations of balance with and without an auxiliary resistance in the circuit. Two different values (500 ohms and 1000 ohms) of this auxiliary resistance were tried and both gave the same result. This result, however, was identical with that originally measured at 1000 cycles. Since the effective electrode capacitance is thus apparently not clearly defined or at least is associated with other effects that could not be identified, no further effort was made to establish the gradient in terms of the total applied voltage and the distance between electrodes, and the gradient determined with the sliding arm was taken as correct.

Electrolyte.- Solutions containing about 0.005 to 0.010 percent sodium chloride in distilled water were used as electrolyte in the tanks. Much smaller concentrations still permitted sharp readings but were avoided because of the relatively large local concentration variations that might result from the solution of traces of conducting matter from the varnish or from the air. Much larger concentrations were also avoided in order to minimize polarization at the electrodes. Tap water was not used because it was found to precipitate considerable amounts of material on standing. Local variations of temperature, which could produce large local variations in resistance, were minimized by covering the tanks, keeping them in a thermally insulated wooden box, and stirring the solutions frequently. When the drift was large or when stirring caused appreciable changes in the readings, the readings were discarded.

Test procedure.- The tank was filled with solution to slightly below the level of the diameter (allowing for the displacement volume of the model) and then carefully leveled until the potential gradient as determined with the standard was uniform along the length of the tank. The model was then lowered into the solution and its height and level carefully adjusted until it was just

half immersed. The adjustment was facilitated by means of marks on the model showing the position of the horizontal meridian. Care was also taken to center the model laterally.

Measurements of the potentials at the six contacts were made in order and repeated in reverse order. The set of readings was repeated several times. The free-stream gradient was measured, with the model in place, at a point some distance in front of the model. The value of the free-stream gradient was considerably less than that measured with the model removed because of the increased resistance of the passage around the model. The field of the model itself caused a negligible correction to this free-stream gradient.

The uniformity of the gradient along the tank was checked after removal of the model.

Precision.- The sensitivity of the bridge was very high; the resistance boxes could generally be set to 0.1 ohm, corresponding to about 0.05 percent of the potential difference between adjacent pairs of contacts on the model. The accuracy of a given set of readings, however, is considerably less than the sensitivity of the bridge, as indicated by the fact that independent tests (involving repetition of the entire procedure) could give results differing by as much as 0.3 percent; and irregularities of the same order appeared in the wall corrections derived from the potential difference measured between the five different pairs of adjacent contacts.

Inasmuch as the wall effect is obtained by comparing the potential differences measured in the largest tank with the potential differences measured in each of the other tanks and since few independent sets of readings were taken, the results might contain twice the inaccuracy of each set. If a further error of perhaps 0.1 percent is allowed in the estimation of the wall effect in the largest tank, a total error of about 1 percent appears to be possible in the correction derived for each pair of adjacent contacts. That the errors will tend to be additive is, however, unlikely; and the average of the corrections for the five different pairs of contacts will, in any case, have considerably better than 1 percent accuracy.

Actual gradients on the model are known only within 2 to 3 percent because the distances between the model contacts could not be measured or, in fact, identified to within 0.005 inch. The wall correction is determined only from the ratios of the gradients and is therefore not affected by inaccuracies in the distances between the model contacts.

RESULTS AND DISCUSSION

Experimental velocity correction.- Curves of the jet-boundary correction to the velocities in the neighborhood of the flap, found by comparing the potential differences between adjacent pairs of contacts measured in the different tanks, are shown in figure 8. The average jet-boundary-correction curve is shown in figure 9. The lowest point of these curves - that is, the correction for the largest tank - was computed theoretically by the methods indicated in the following paragraph.

Comparison with theoretical correction.- Lamb (reference 1) showed how to compute the flow about a Rankine ovoid in a cylindrical tank. These methods were used to provide the correction for the largest tank, and also to compare the experimental results with those that could have been predicted for an ovoid of roughly the same dimensions. The longitudinal distribution of cross-sectional area for the nacelle model is shown in figure 10, together with the distribution for the assumed equivalent ovoid, which had the same maximum cross section, a somewhat greater volume, and a somewhat smaller length. (An ovoid with the same maximum cross section and length would have had an excessive volume and a compromise of this type was considered most reasonable.) The computations were made for point B on the ovoid, the longitudinal distance of which from the upstream focus is 0.17 times the distance between foci, or 0.58 times the maximum diameter. The results have been plotted together with the experimental results in figure 9. The agreement is within practical accuracy over the entire range. The agreement, however, depended to some extent on the location of point B. If the point had been chosen at the middle of the ovoid instead of near the end, the correction for the smallest tank would

have been 32 percent instead of 24 percent, or one-third higher; for the larger tanks, however, the relative difference would have been somewhat less.

Application.- According to equation (1), the correction to the pressure coefficient follows from

$$\frac{1 - P_{tunnel}}{1 - P_{free\ air}} = \frac{(V/V_o)^2_{tunnel}}{(V/V_o)^2_{free\ air}}$$

For example, where for a typical nacelle in the 16-foot tunnel (velocity correction = 1.08) a pressure coefficient of -0.75 is observed, the corrected pressure coefficient is -0.50, as given by the equation

$$\frac{1 - (-0.75)}{1 - P_{free\ air}} = (1.08)^2$$

The pressure coefficients for the model are shown in figure 11 for the two smallest tanks and for the free-air condition. For the free-air condition, the suction indicated for the region of the flap tip seems about normal.

CONCLUSIONS

Jet-boundary corrections to cowling-flap-outlet pressures have been studied by an electrical-analogy method, and the corrections found have been presented as a function of the ratio of wind-tunnel diameter to effective nacelle diameter. The correction in the LMAL 16-foot high-speed tunnel for a typical 5-foot nacelle with 12-inch-chord flaps extended 30° is about 0.25 times the free-stream dynamic pressure. Comparison of the results with theoretical values for a source-sink ovoid in a circular tunnel showed approximate agreement.

It was found that accuracy in the electrical tank requires that only the nobler metals be used for the electrodes. Wire contacts for probing the solution potentials should be of platinum.

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3. Malavard, Lucien: Étude de quelques problèmes techniques relevant de la théorie des ailes. Application à leur solution de la méthode rhéoélectrique. Pub. No. 153, Pub. Sci. et Tech. du Ministère de l'air (Paris), 1939.

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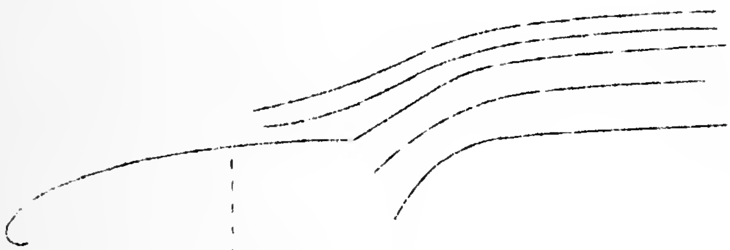
(a) Current flow



(b) Air flow

Figure 1.- Constrast between flow of air and flow of electric current at a cowl flap.

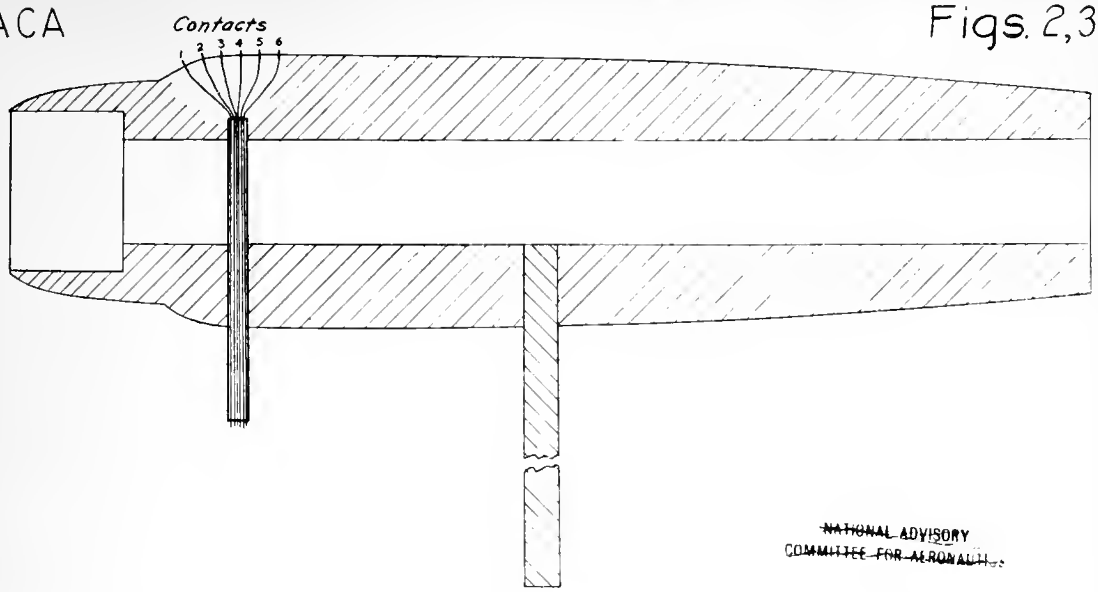


Figure 2.- Nacelle model, showing positions of platinum contacts.

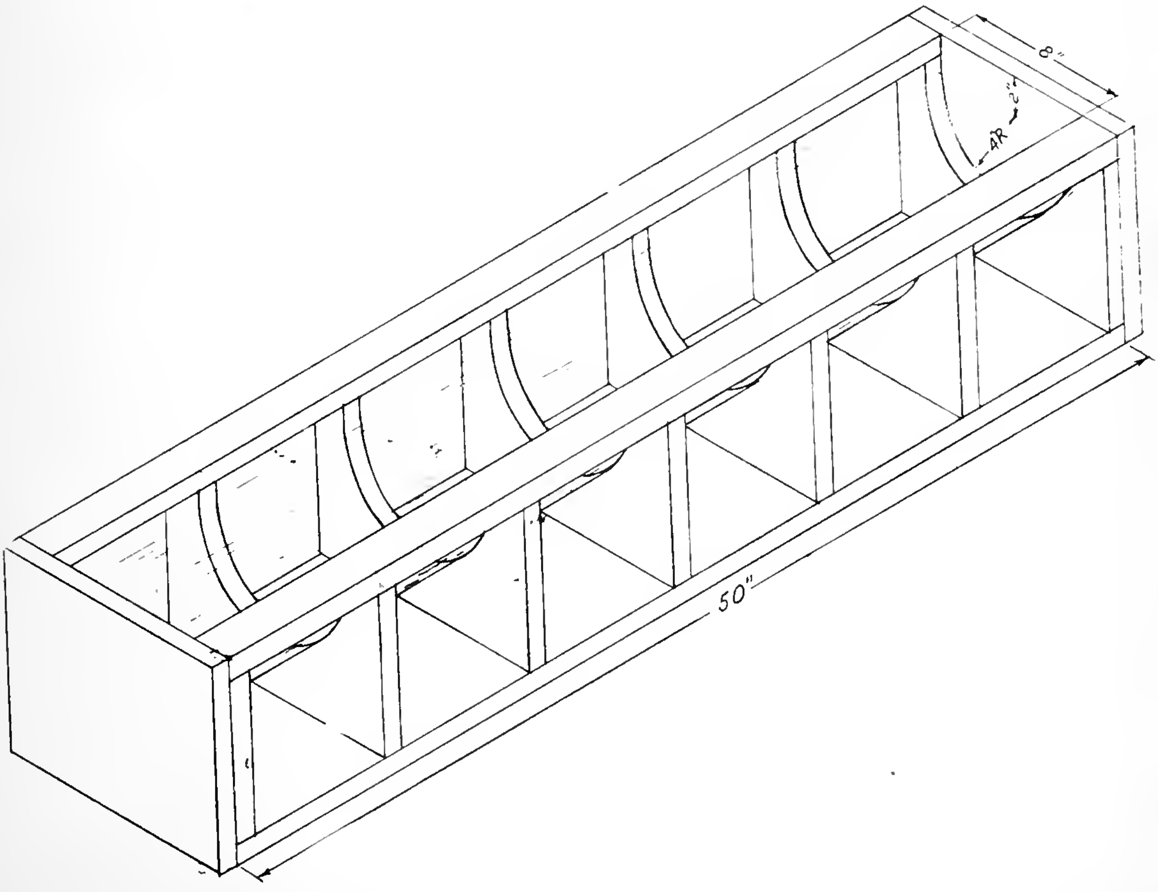
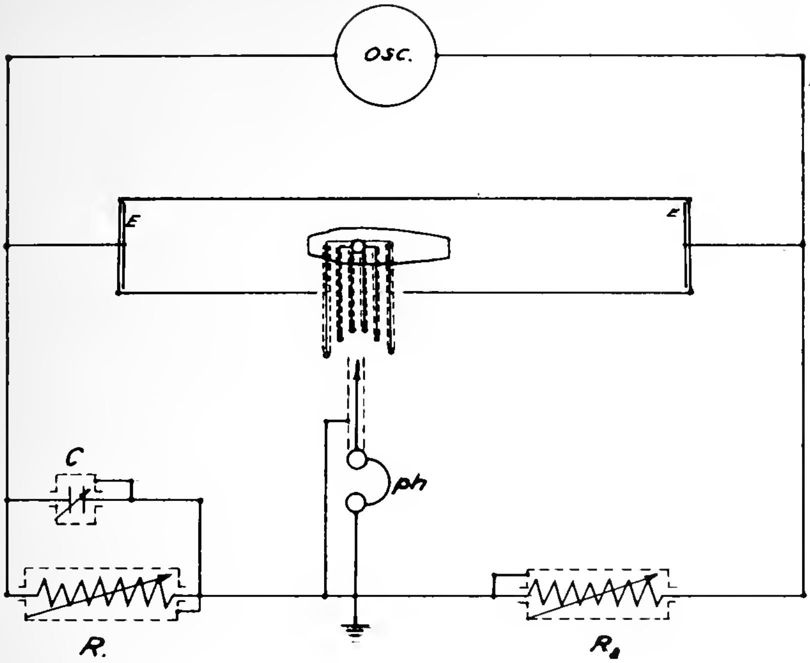


Figure 3.- Sketch of 8-inch tank



R_1, R_2, decade resistance boxes, 0-10,000 ohms.

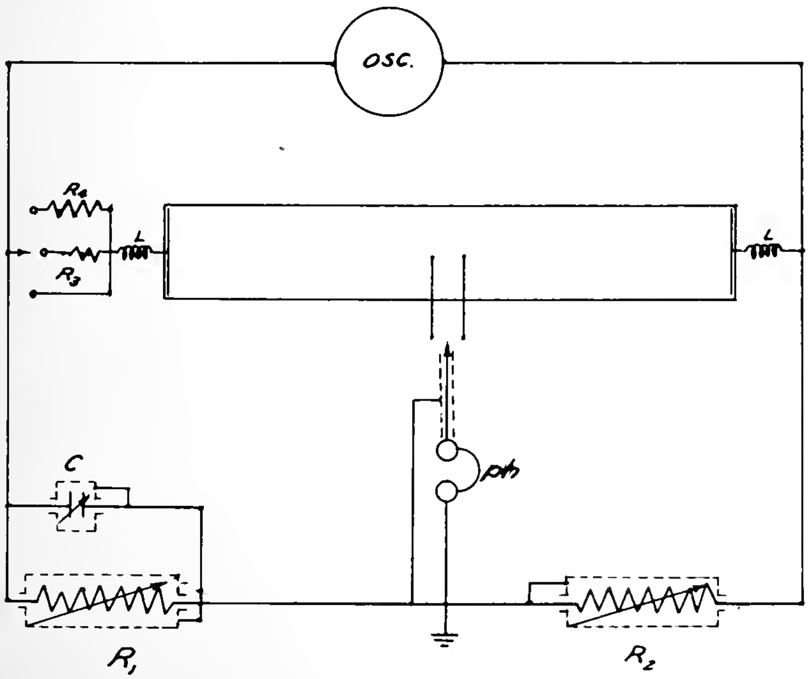
C, variable capacitance 0-0.0015 mfd.

ph, headphone detector

osc., audio power oscillator (5 watt).

E, tank electrodes

Figure 4.- Diagram of circuit



R_3, 500 ohms
R_4, 1000 ohms

L, air inductor about 15 mh.

Frequency of oscillator adjusted for maximum current flow in tank.

Figure 7.- Circuit for elimination of errors due to polarization at electrodes.

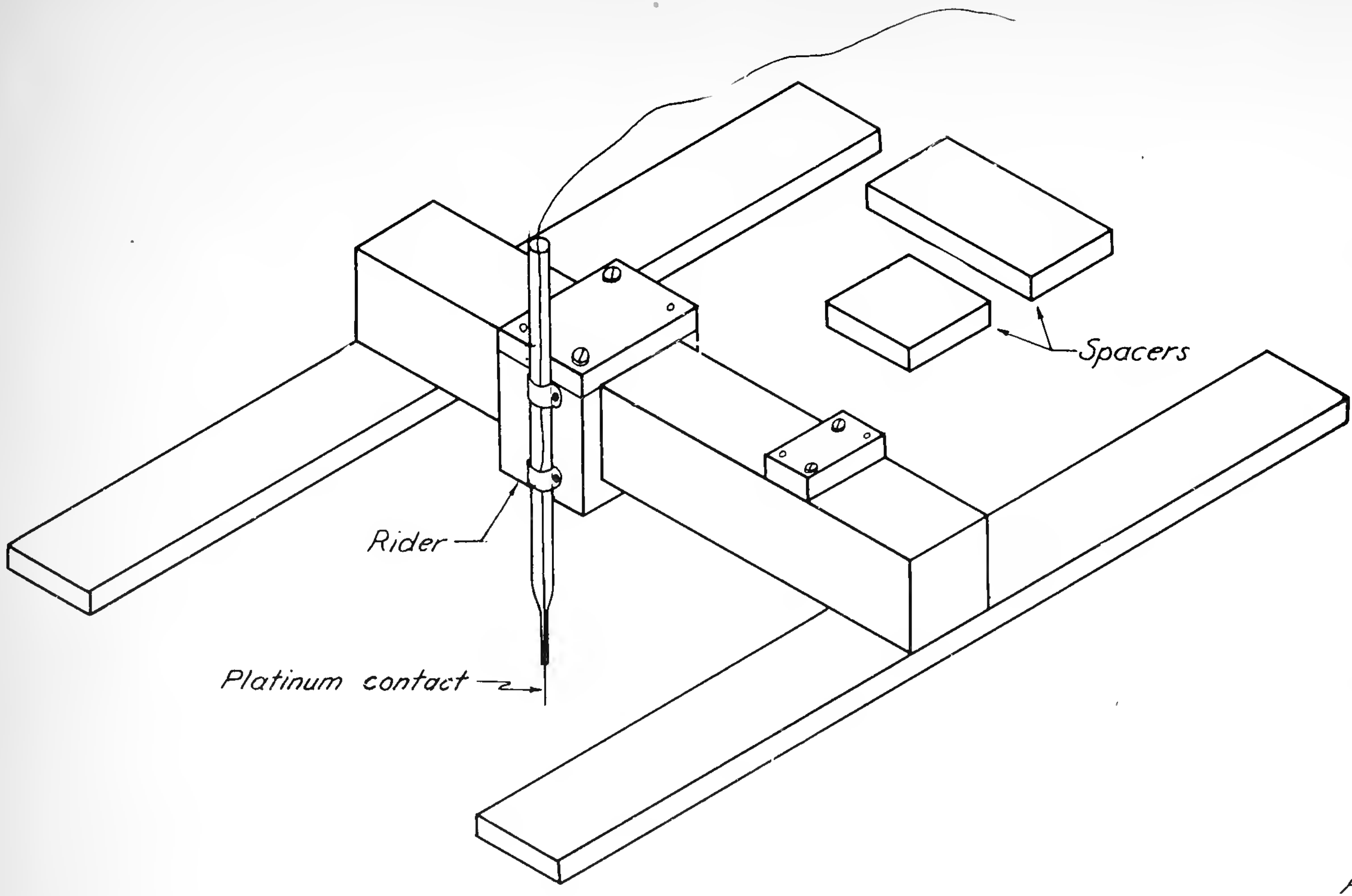


Figure 5-Primary distance standard.

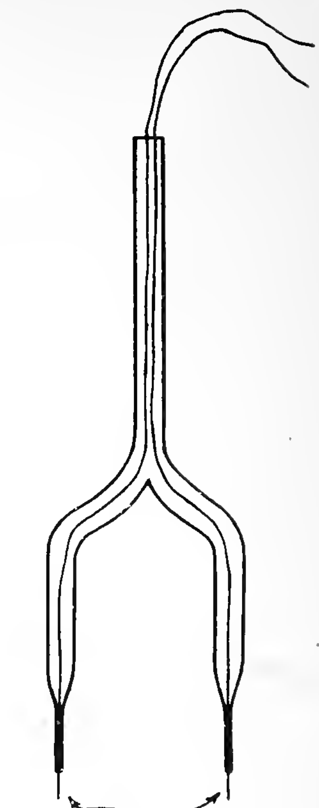
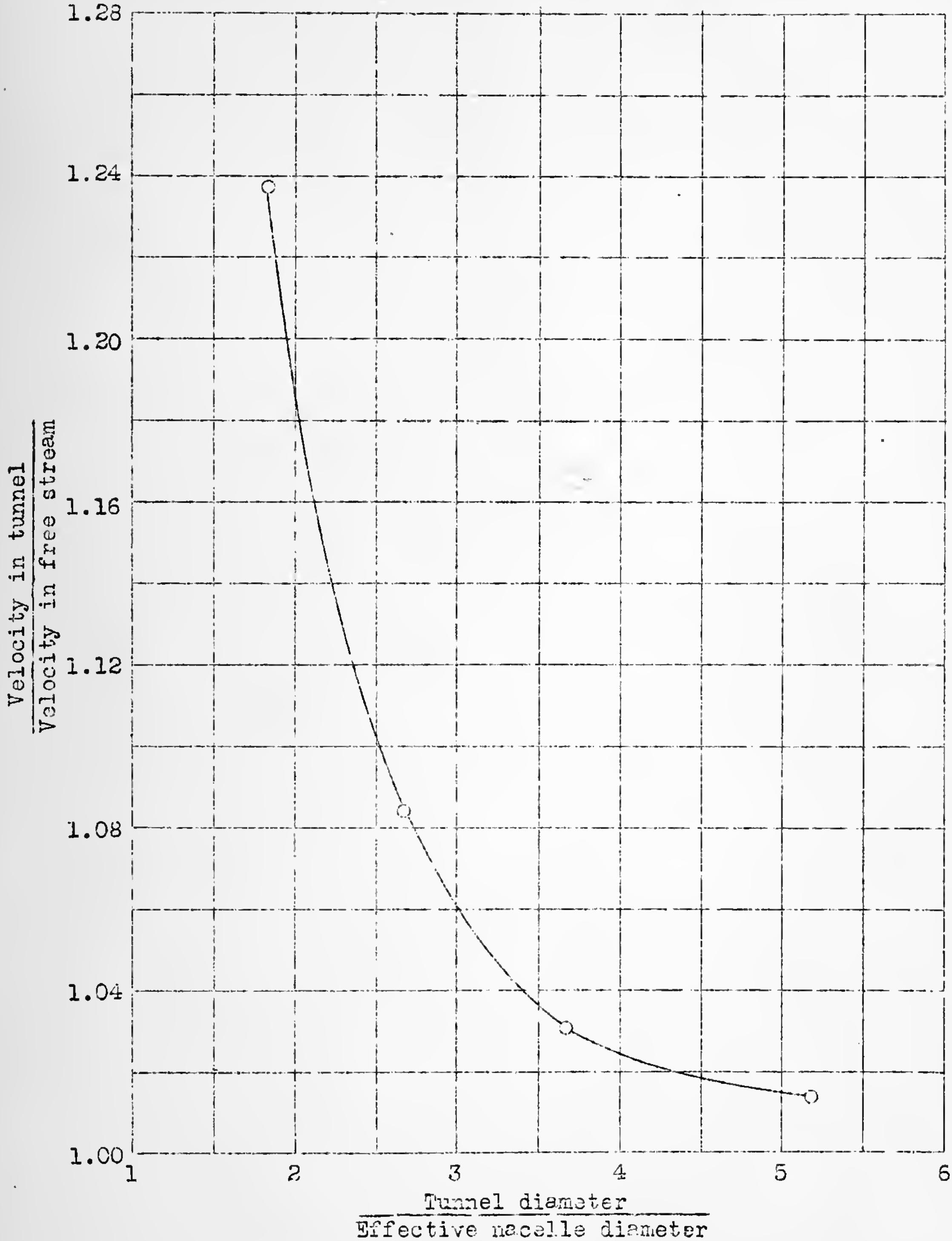
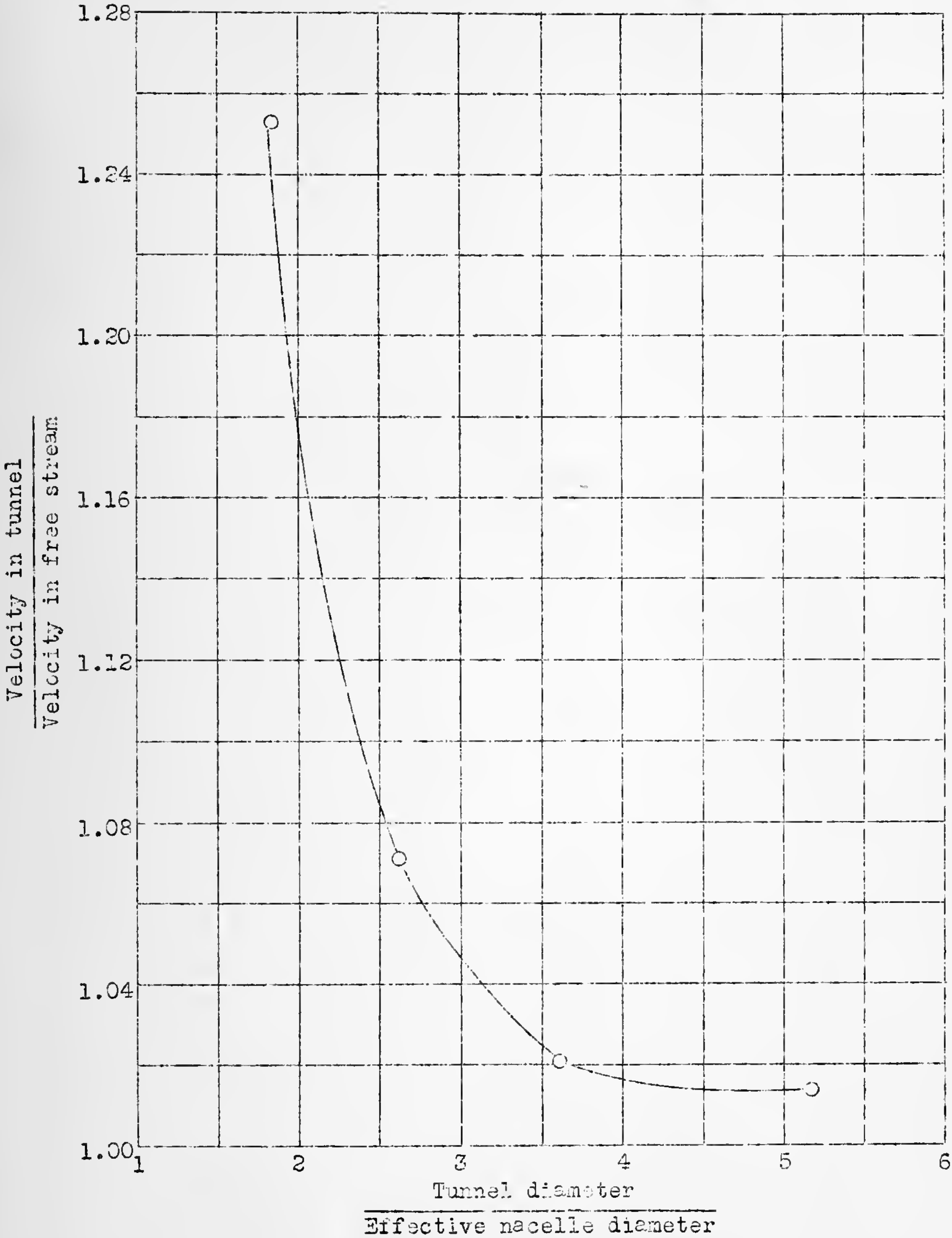


Figure 6-Secondary distance standard.



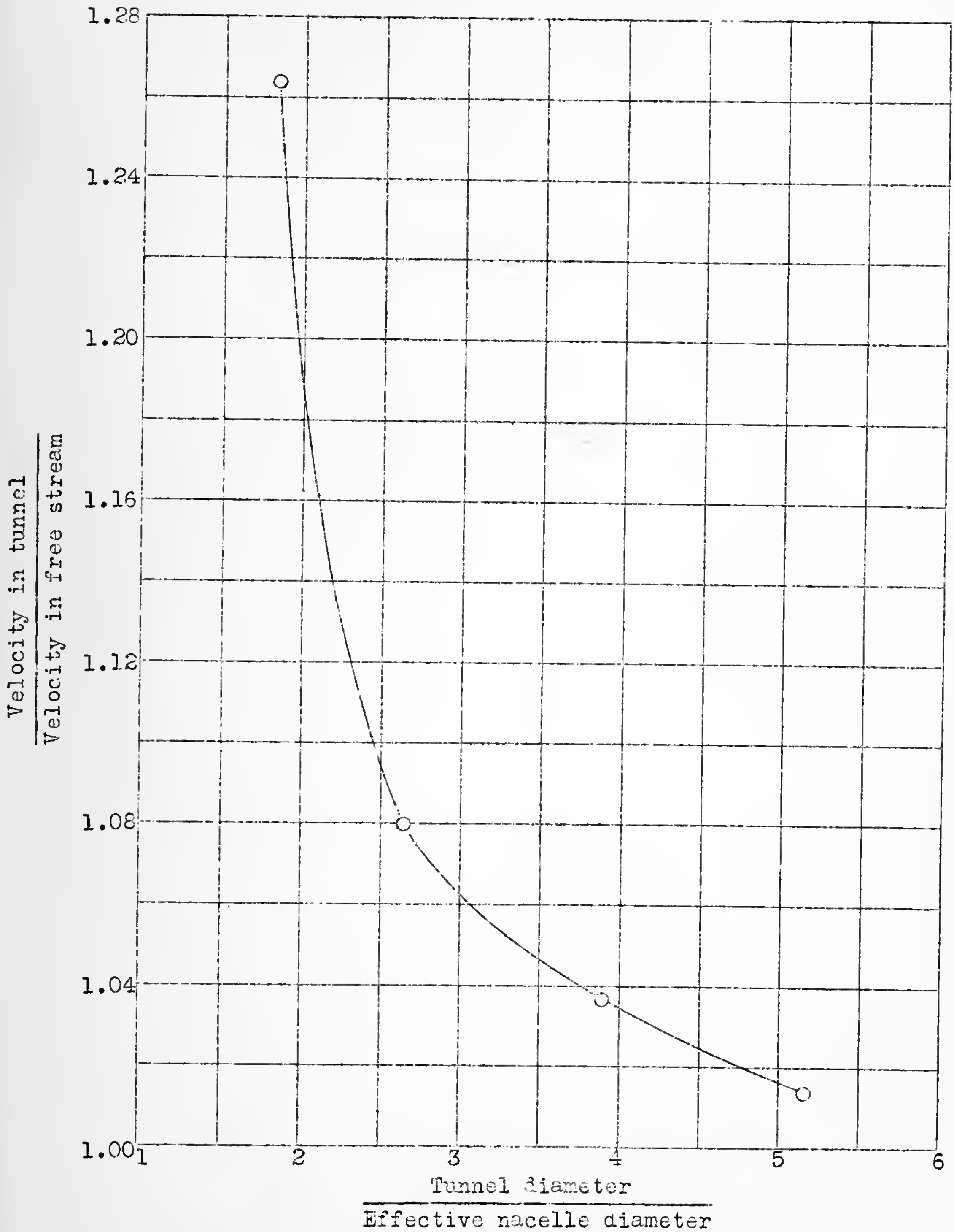
(a) Contacts 1 and 2.

Figure 8.- Wall effect on mean velocity between adjacent pairs of contacts.



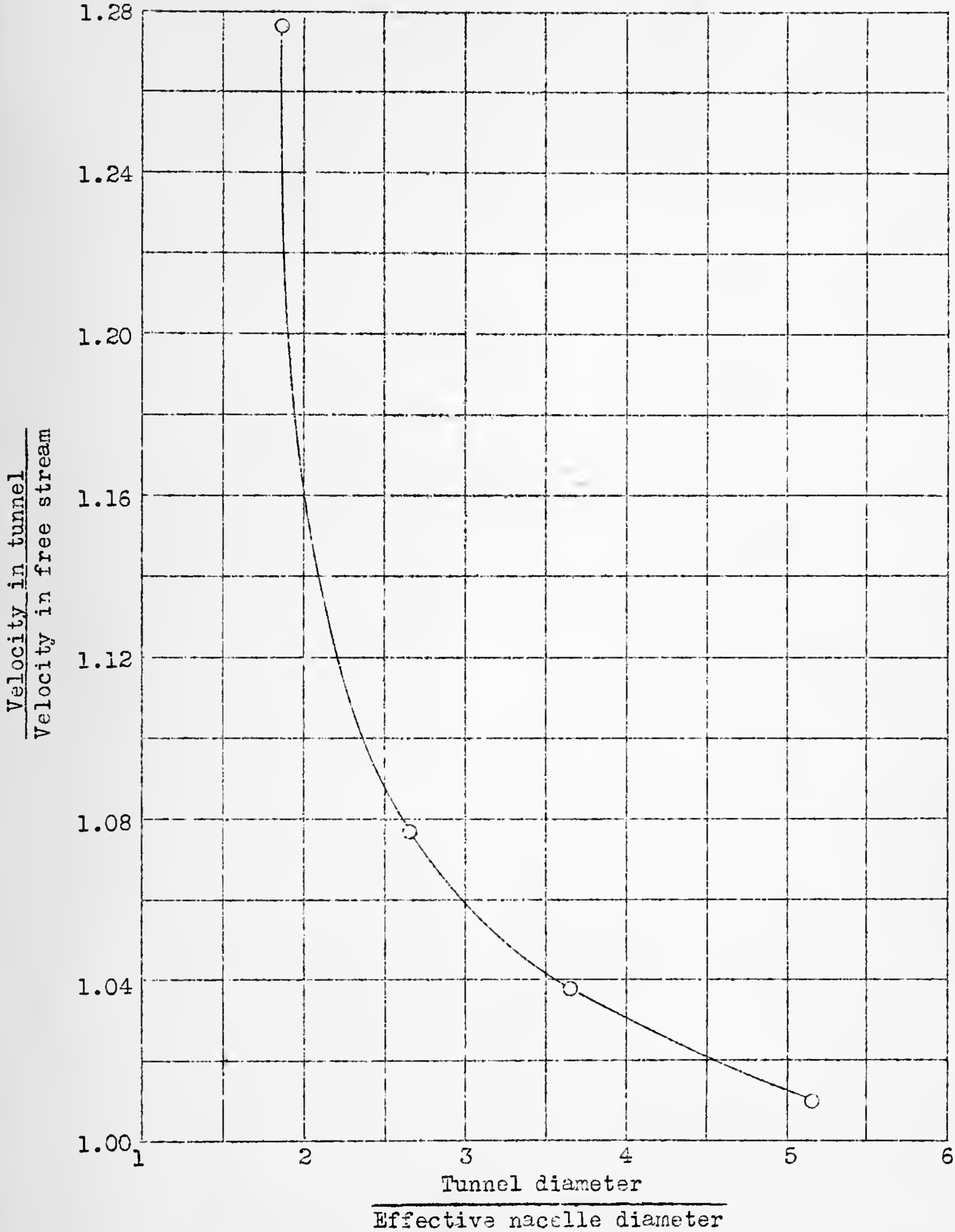
(b) Contacts 2 and 3.

Figure 8.- Continued.



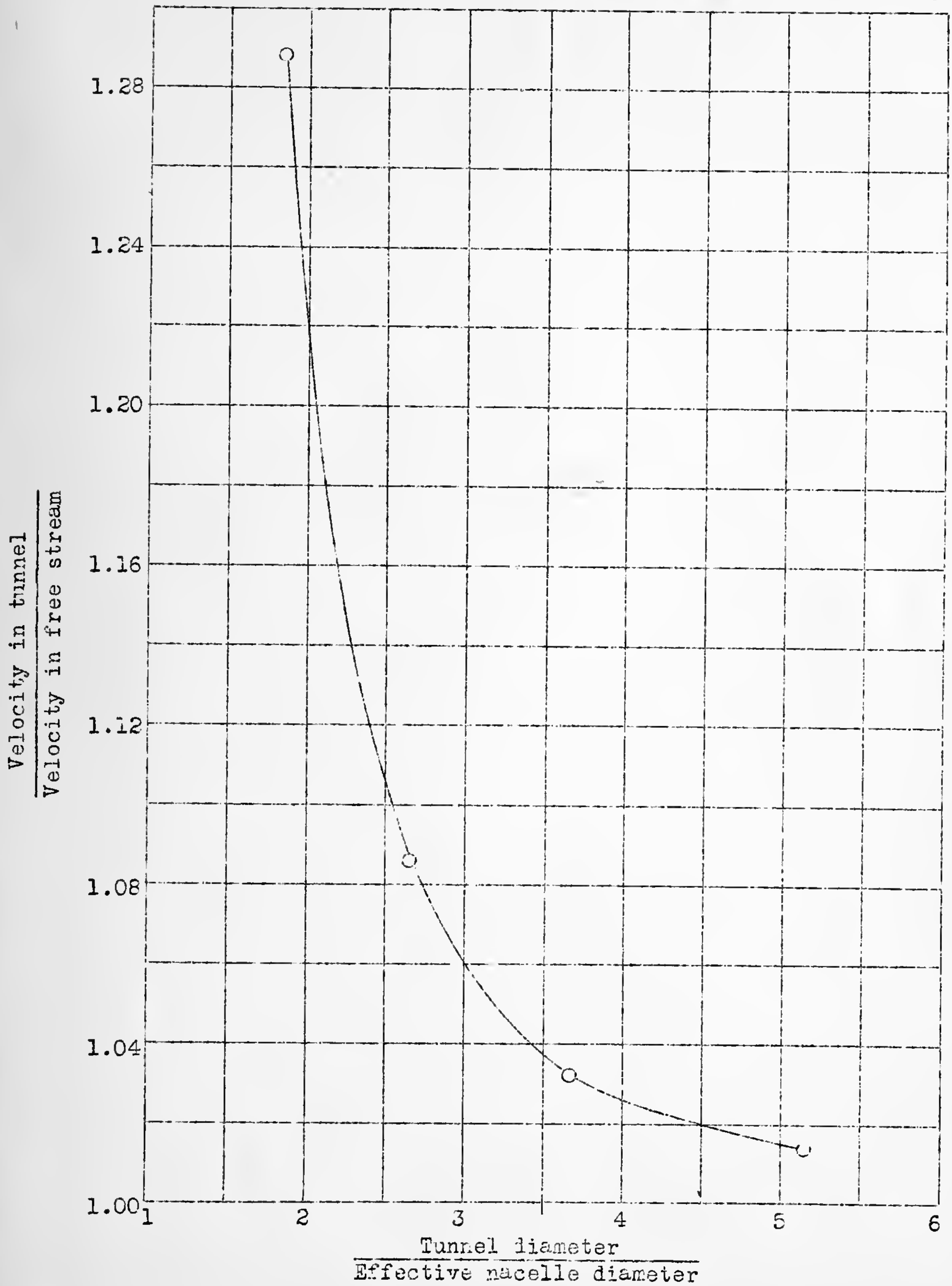
(c) Contacts 3 and 4.

Figure 8.- Continued.



(d) Contacts 4 and 5.

Figure 8.- Continued.



(e) Contacts 5 and 6.

Figure 8.- Concluded.

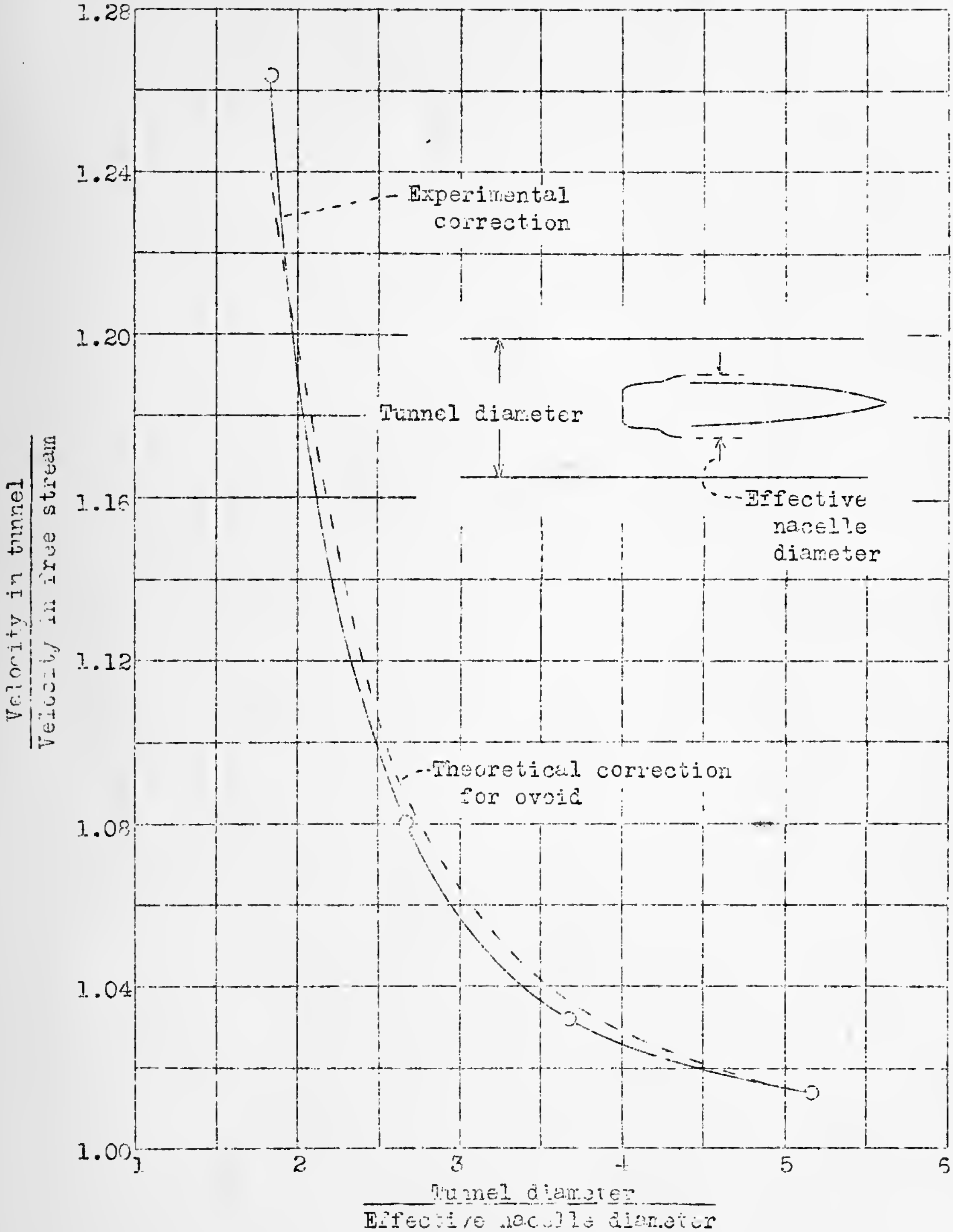


Figure 9.- Mean wall effect on velocities in region of cowl-flap tip, and corresponding theoretical correction for point B of the ovoid of figure 10.

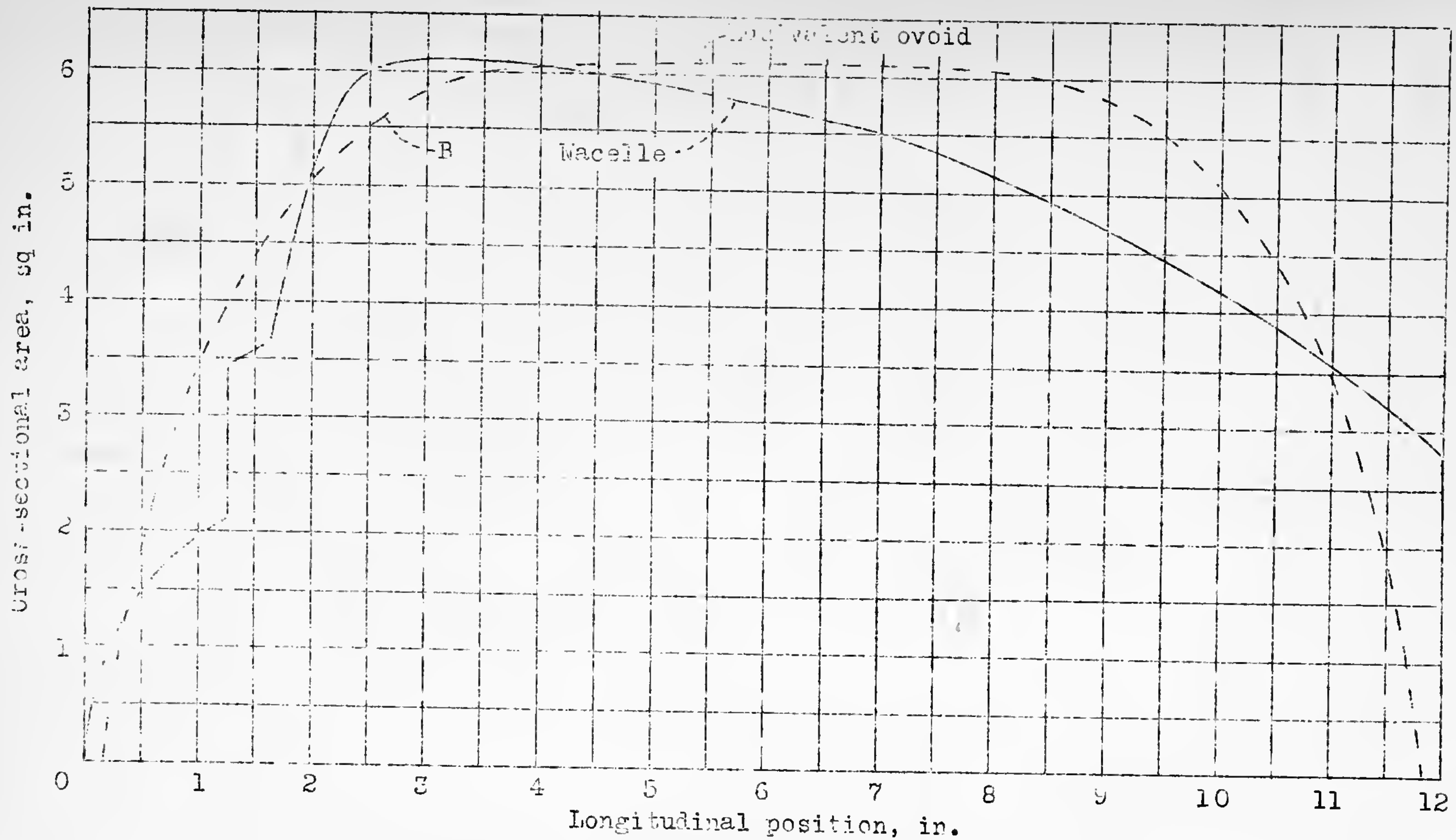


Figure 10.- Longitudinal distribution of cross-sectional area for nacelle and for assumed equivalent ovoid. Point on ovoid for which corrections were computed is indicated as B.

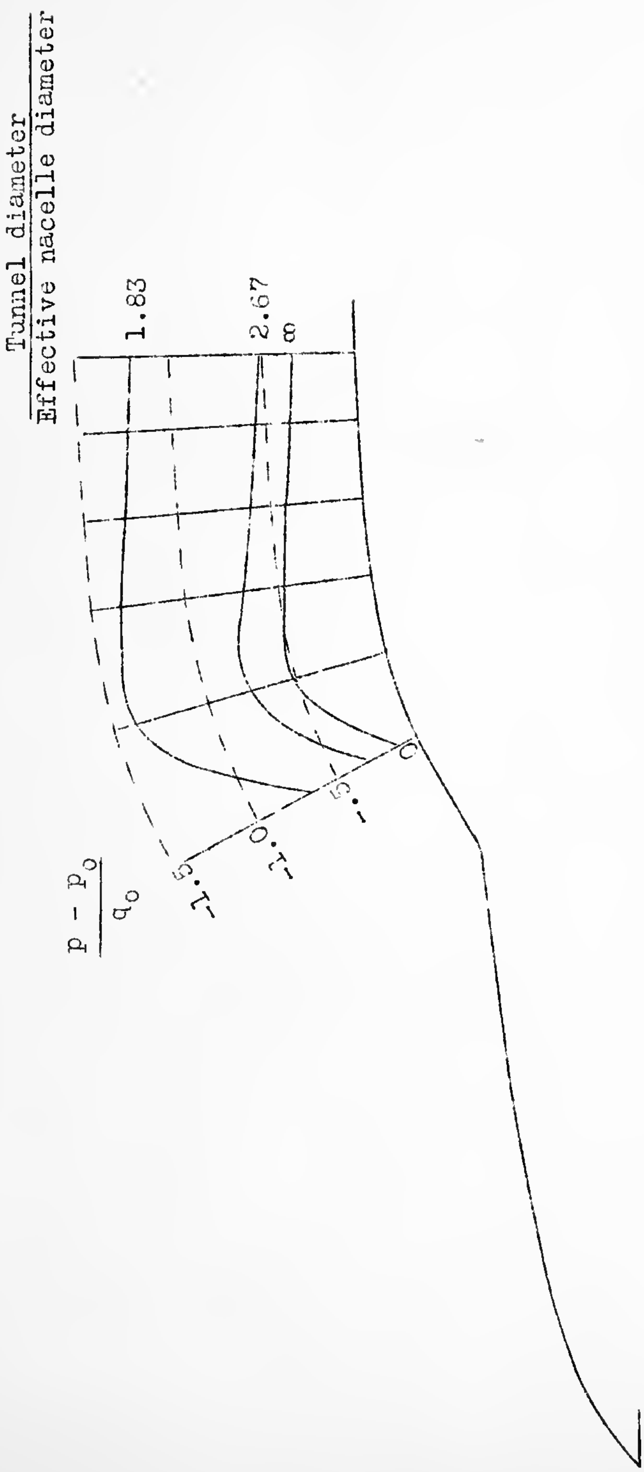


Figure 11.- Pressures near the cowling-flap outlet.